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Optimizing State of Charge (SOC), temperature, and State of Health (SOH) of lithium-ion batteries

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ABSTRACT

Li-ion Batteries (LiBs) explode when there is uncontrolled/regulated charging, thus leading to gradual/catastrophic failures. Dendrites (electrical short inside a battery/cell) are also formed when LIBs is charged with high current. During discharge process, if the battery goes below a set low cut voltage, it will lose some capacity permanently or even explode as evident in the case of Samsung note 7. The paper is on design and optimization of li-ion batteries using MATLAB/SIMSCAPE. A constant current and constant voltage profile source is used in charging the battery pack which consists of three li-ion batteries connected in series. Each cell has a bleed resistor connected in parallel to it to perform balancing. The SOC of each battery is balanced by the system estimate of SOC of each cell/battery from the open circuit voltage (OCV). Constant current I (A) is used to charge the battery using 15A and it is applied until the terminal voltage reaches the open circuit voltage (OCV) level and switch to constant voltage charging. The constant voltage is maintained till the current reduces to zero (0). The charging system considers three parameters: the State of Charge (SOC), State of Health (SOH) and the Temperature of the batteries during charging. The temperatures and thermal energy of

the batteries during charging is also tested. During simulation, initial temperature of each battery was kept at 20^0C. The battery voltage and current were measured. The charging system balances the SOC of each cell, in other to enable the three batteries to charge at the same voltage. Thermal properties of the battery are also considered to prevent the battery from aging.

Keywords: Li-ion Batteries, open circuit voltage, Constant current

1. INTRODUCTION

Electrical energy is an indispensable need of present technology- psyched world; though, Sub Saharan Africa is characterized by poor power supply, power irregularity, low voltage supply, load shedding and a whole lot of let downs by power generation and distribution corporations. These have increased the dependence of population on alternative battery-driven sources of electrical energy such as dc-ac converters and photo voltaic systems. Hence, the Electrical/Electronic Engineering field has been inundated with studying battery technology in order to design more efficient batteries and its management system. In lithium ion batteries (LIBs), lithium ions move from anode (negative pole) to cathode (positive pole) during discharge and from cathode to anode during charge process. During discharge process, if the battery goes below a set low cut voltage, the battery will lose some capacity permanently as evident in the case of the fire incidents that occurred in Tesla model in electric vehicle and Samsung note 7 due to explosion of the batteries (Aylin, 2018). The charging current, discharge rate, discharge limit and operating temperature are sensitive matters in LIBs. Economic losses of high magnitude also arise from collapse of battery bank due to single weak battery which has been charged/discharged repeatedly beyond safe operating limit. Battery bank or string is as good as its weakest battery/cell (Battery University, 2018). It is difficult for series connected string of batteries to have all the cells/batteries at the same voltage or SOC due to manufacturing process and ageing. The string is not balanced under this condition. An imbalance is a serious issue for a string of LIBs, so a system to take care of this need to be developed as regular charger cannot balance the batteries/cells. The aim of this paper is optimization of Li-ion Battery Management System (BMS) with specific objective to design BMS to achieve the following:

- Deduce SOC, SOH and battery temperature.
- Show and equalize individual SOC of batteries that are not balanced
- Control charging current and discharge limit
- There are different methods of designing/developing BMS. For the purpose of this paper, a microcontroller is used for the design. SOC of individual cells will be monitored and balanced. Readings of battery voltage is converted to SOC using discharge curve (Voltage vs. SOC) of LIBs and it is designed and manufactured with different specifications but this paper is limited to BMS that can handle 3 serially connected units of 3.7V, 60Ah li-ion cells because of its wide usage. BMS will be able to equalize the voltages of all the cells.

The significance of this paper is as follows:

- Save money spent on replacing prematurely failed battery banks and systematic upgrade of battery bank,thus obtaining a more cost effective and reliable battery bank.
- Improved and real time monitoring of individual batteries/cells SOC.
- Equalize the charge of cells/batteries that have abnormal charge in a string.

Review of Relevant Literatures

LIBs are rechargeable and are known for high energy density, light weight and longevity. Proper care needs to be taken for its optimum performance to be achieved. As a comparison, average LIBs can store 150 watt-hours of electricity in 1 kilogram of battery – A nickel-metal hydride battery of the same weight can store between 60 – 100 watt-hours and lead-acid battery only 25 watt-hours (Jeffrey, 2018). The economic viability of rechargeable batteries is due to its potentials to be charged and discharged several times. To ensure that the batteries operate up to its rated service life within safe limit, the need for an external intelligent system arises. This external system known as Battery Management System (BMS) controls and improves performance of the batteries. BMS serves as an interface between batteries and users, and its main object is the rechargeable battery. During operation, BMS monitors and control the status of battery cells such as cell temperature, cell voltage, State of Charge (SOC), State of Health, charging or discharging current. BMS helps in prolonging battery service life and enhancing its performance. SOC is usually displayed to the user in a graphic bar or in percentage. In the latter case, 100% implies full battery state and 0% the empty state (Pop *et al.*, 2008). Battery measurements and modeling are done to deduce SOC. When SOC of LIBs is estimated properly, it will improve battery life and performance respectively (Bizhong *et al.,* 2017). Although SOC of a battery gives information on available maximum possible charge

in a rechargeable battery, which is normally expressed in percentage, in consideration of batteries in use, estimating the State of Health (SOH) is integral to knowing its performance as compared to a new one. According to (Leijen, 2015), SOH performs the function of indicating when battery is aging. The researcher further revealed that SOC describes total dischargeable charges in a battery until cut off terminal voltage is hit; at this point the battery tends to have lower capacity. Uncontrolled charging of LIBs leads to rapid failure and /or explosion of the battery (Zoe, 2016). Dendrites are also formed when LIBs is charged with high current. Dendrite is an electrical short inside a battery/cell.

State of Charge (SOC)

SOC of a battery is expressed and defined as percentage of the maximum possible charge that is present inside a rechargeable battery. It is the percentage of the full capacity of a battery that is still available for further discharge. SOC measures energy remaining in a battery. It is essential for battery modeling and management. Developing efficient and correct SOC algorithms is always a difficult thing to do and most existing works use regressions based on circuit model, with time-variant characteristics, which in most cases may not apply to different battery types and finds it difficult to converge. This is shown in equation 2.6 (Pop *et al.,* 2005) as:

$$SOC(\%) = SoC\epsilon f + \frac{Qcbg}{Qmax} * 100$$

Where $Qcbg$ is the remaining charge in the battery, $Qmax$ is the maximum capacity, and $SoC\epsilon f$ is the initial SoC before charging. For example, a fully charged battery has SoC of 100%, and SOC of 0% when totally discharged. SOC is an important parameter used to describe the performance of batteries (Wen-Yeau, 2013).

State of Health (SOH)

SOH is reflection of a battery's general condition and its capacity to deliver the specified performance/power in comparison with a new battery. A battery may be in a poor SOH because of corroded electrode (catastrophic failure) or may simply be suffering from loss of capacity due to electrolyte stratification, which may be overcomed through a period of overcharge allowing the full capacity of the failing battery to be recovered (recoverable failure) (Pritpal, 2002). SOH of battery reveals if a battery should be replaced or not. It determines if the battery is aging, as well as wearing out. According to (Juang, 2010), battery should be replaced if its SOH is reduced to 80% of the original. This is usually determined by an arbitrary cut off voltage.

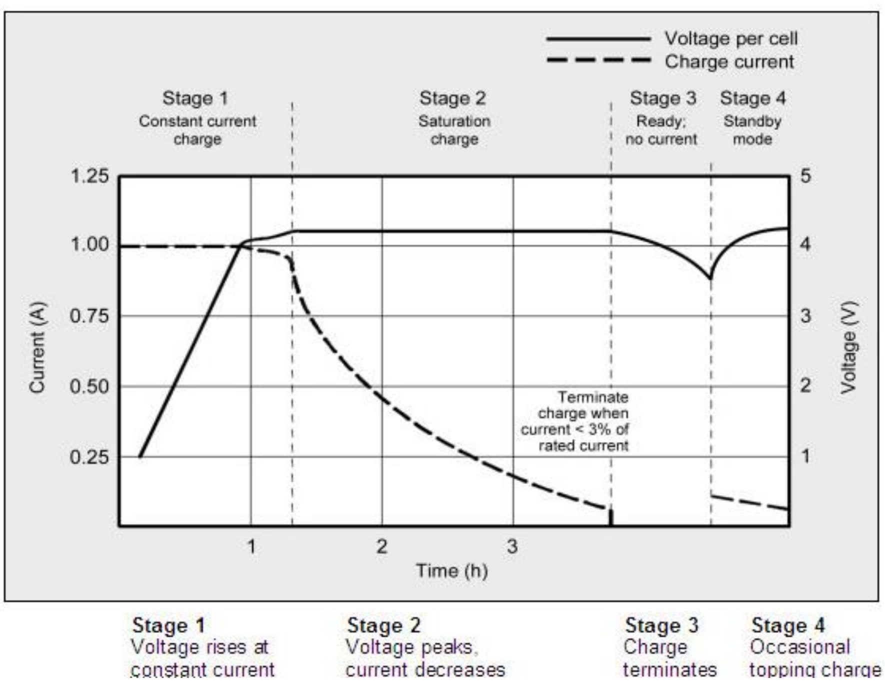


Figure 1 Diagram showing charge process of li-ion battery (Battery University, 2015)

Cell/Battery Connections

The two main types of cell connection are: series and parallel connection. In a big battery bank or pack, the two schemes are usually applied. Series connection is used in application that requires high voltage. When there is an open circuit in any of the cell/battery, the string fails. If it is a short circuit, the overall voltage of the string will drop. Parallel connection is utilized in an application that requires high current. When there is an open circuit in any of the cell/battery, the string does not fail; instead the load will draw higher current from other cells. This may damage the remaining cell if they cannot handle it. If it is short circuit fault, other cells will be discharged through the bad cell.

Battery Charging

There are several methods of charging batteries/cells. These include; constant current charging, constant voltage charging, pulse charging, float charging and trickle charging. For li-ion cell/battery, the common charging methods are constant current and constant voltage charging approach. Li-ion batteries are known to give an excellent performance. There must be correct charging for the best performance to be achieved. If li-ion battery is not charged in a proper manner, the battery operation can be diminished or may even be destroyed, thus care must be taken.

In Figure 1, a constant current constant voltage (CCCV) charger first applies constant current rate until the battery reaches a set-point voltage, charging current is then reduced to maintain the set-point voltage (Simpson, 2011).

2. METHODOLOGY AND DESIGN ANALYSIS

Li-ion battery is modeled using an EMF source, and a time constant unit. (3)Li-ion batteries/cells are used as battery pack, and are connected in series. BMS makes use of constant current constant voltage source (CCCV) in charging the pack; cell balancing is achieved using Logic State Flow (LSF) algorithm. The LSF is used in controlling the charging rate and discharge limit of the battery pack. Constant voltage and constant current source is used in charging the battery pack. The battery pack consists of three li-ion batteries connected in series. The major function of the sensing unit is to monitor the battery voltage as well as heat dissipated during charging. Li-ion battery parameters used for the design are shown in Table 1.

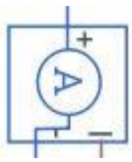
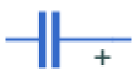
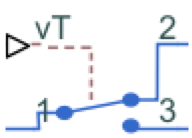
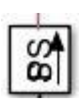
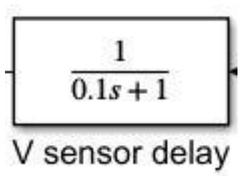
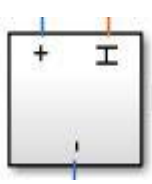
Table 1 Li-ion battery parameters used for the design

Battery Parameters	Empirical Values
Nominal Capacity	60Ah
Nominal Voltage	3.7V
Internal Impedance	1khz AC
Charging Cut-off Voltage (CCCV Model, V)	4.5V
2000 Life Cycle	(0.3C Charging-Discharging, 80% DDC)

The main Simulink components used for the simulation are as shown in table 2.

Table 2 Simulink Components

Graphical block	Name	Use
	Resistor	This block is used to simulate standard resistor
	Scope	Displays input signal with respect to simulation time

	Logic controller	This block is used to simulate the logic flow diagram
	Diode	This block is used to simulate a standard diode
	Current sensor	This sensor converts current into physical signal proportional to the current.
	Voltage sensor	This sensor converts voltage into a physical signal proportional to the voltage.
	Constant	This block creates a physical signal constant: y = constant
	Capacitor	Models a linear capacitor
	Single phase, two way switch	The block represents a Single-Pole Double-Throw (SPDT) switch controlled by an external control signal vT. If vT is greater than the threshold, then the switch common port 1 connects to port 3, otherwise it connects to port 2.
	Simulink-PS converter	Converts the unitless Simulink input signal to a Physical Signal
	PS-Simulink converter	Converts the input Physical Signal to a unitless Simulink output signal
	Transfer function	The numerator coefficient can be a vector or matrix expression. The denominator coefficient must be a vector. The output width equals the number of rows in the numerator coefficient.
	Battery pack	This block is used to simulate the batteries/cells
	Electrical reference (ground)	This block is used as an electrical reference port. A model must contain at least one electrical reference port (electrical ground)

Simulink Battery Modeling

There are different approaches to modeling and characterizing batteries. In the course of developing BMS algorithms in Simulink, equivalent circuits were used to simulate thermo-electric behavior of the cell. The equivalent circuit usually comprises of voltage source, series resistance, and one resistor-capacitor pairs in parallel. The voltage source serves as the open circuit voltage while the other components model the internal resistance and time dependent behavior of the cell. Randle's 1st order electric equivalent is used. The equivalent circuit is used in simulating the battery pack in this work (figure 2).

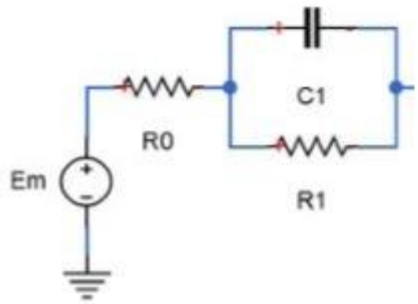


Figure 2 Randle's 1st Order Equivalent Circuit of a Battery

Design Analysis

The model describe individual component used in design of BMS and it is shown in Figure 3.

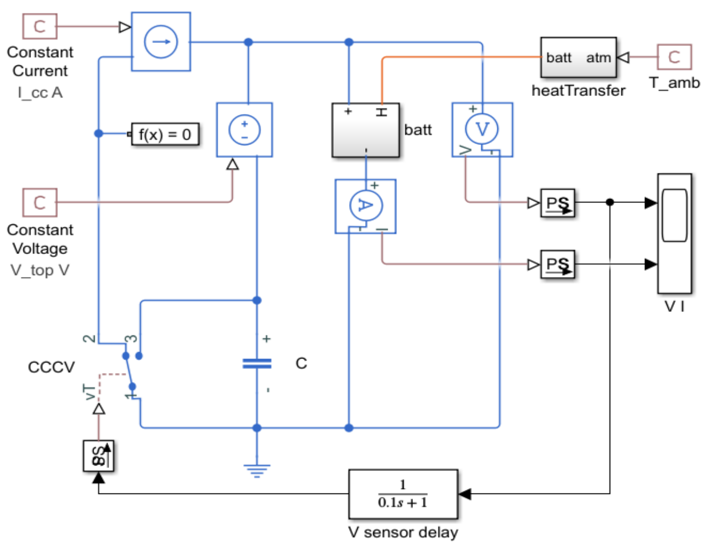


Figure 3 Simulink model of BMS

Constant Current Constant Voltage Source

Li-ion pack is charged using CCCV profile. The SOC of each battery is balanced by the system. Constant current I (A) is used to charge the battery using 15A and it is applied until the terminal voltage reaches the open circuit voltage (OCV) level and switch to constant voltage charging. The constant voltage is maintained till the current reduces to 0. The switch CCV allows the signal to switch from current control to voltage control.

Battery Pack

This consists of 3 Li-ion batteries connected in series electrically and thermally. Each cell has a bleed resistor connected in parallel to it to perform balancing. The schematic diagram is shown in Fig 4.

BMS makes use of bleeding resistor and Light Emitting Diode (LEDs) in the stability of the battery system. The SLF system is used to regulate SOC of individual battery during charging. SLF is a system which controls the cell balancing of individual batteries, in order for the battery to have the same SOC during charging. In the case where SOC of a battery is higher than the other in a pack, the battery is then discharged at a time rate controlled by the SLF control system. The battery is discharged using bleed resistor, LED

and MOSFET. MOSFET controls resistance via its gate by biasing the signal from the SLF system. This made it possible for individual battery to be charged and evenly balancing of SOC. The schematic diagram of the component used to design the battery is shown in Figure 4.

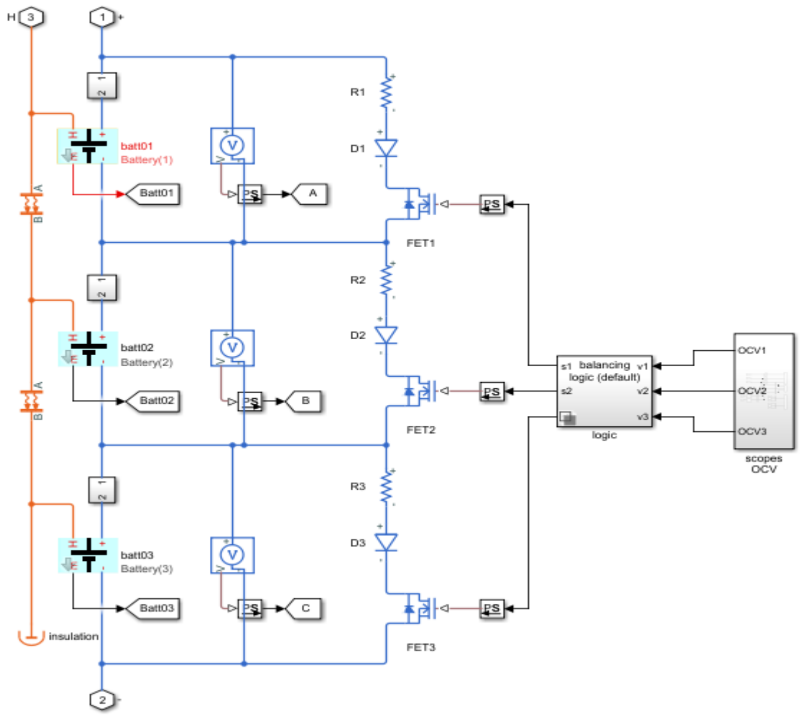


Figure 4 Li- ion battery pack model

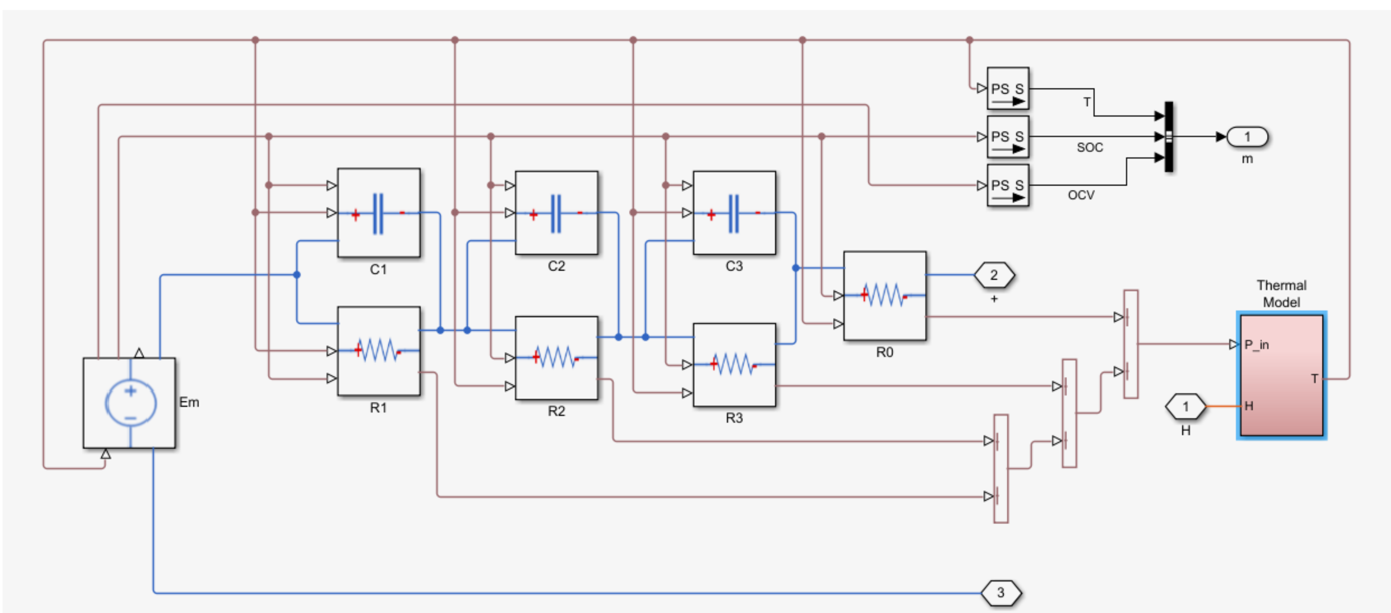


Figure 5 Modeling of complete Li- ion battery

From Fig 5, it shows that Li-ion battery is modeled using an E.M.F source, a time constant and internal resistance of the battery. In Figure 5 the Em is the E.M.F block, resistors (R1, R2 and R3) and capacitors (C1, C2 and C3) are the time constant block (Delayed Response) and R0 is the internal resistance (instantaneous response). This causes instantaneous voltage drop when the battery is loaded.The calculation used in designing the charging system for the battery is as stated.

Individual battery voltage = 3.7 volts and when fully charged = 4.2 volts,

Number of battery/cell = 3

Total voltage = 4.2 x 3= 12.6 volts.

12.6V was applied across the battery terminals at charging current (Icc) of 15A. The voltage and current are sent to both the controlled voltage and controlled current sources respectively and then applied to the battery. This enables the constant current and voltage charging system.

Sensing Unit

The sensing unit is made of current, voltage and thermal detectors. The voltage sensing unit determines the amount of voltage across the individual battery terminal, whereas heat dissipated by the battery during charging is detected by thermal sensing device.

Balancing Logic/State Logic Flow Control System

Figure 6 is the balancing logic that controls the battery/cell balancing in the logic controller. This is a key part of the BMS.

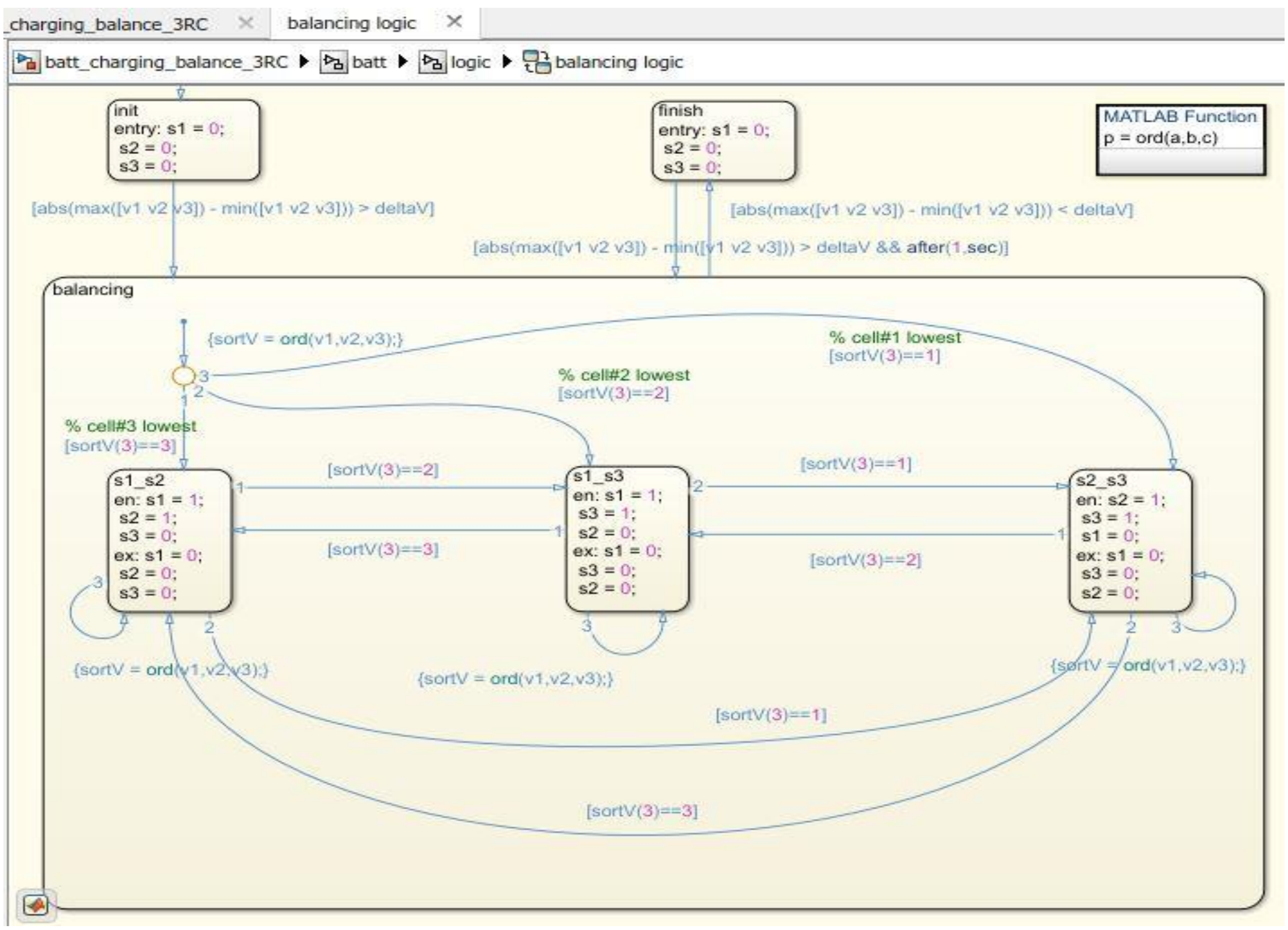


Figure 6 Cell Balancing Logic

Heat Transfer Unit

The major function of heat transfer unit is to detect and cool off dissipated heat from battery during charging. This is used to control the battery SOC during charging of the battery. It reduces the ageing process of the battery and enables it to be charged without the temperature increasing beyond 37 degrees Celsius. PS block measures and converts voltage and current from battery into unit less signal.

SOC Estimation

Data in table 3 is coded into the logic controller to be able to estimate the SOC of each cell/battery from the open circuit voltage (OCV). This table is derived based on charge and discharge characteristics from Figure 5.

Table 3 Voltage vs SOC look up table

Cell OCV(V)	SOC (%)	Cell OCV(V)	SOC (%)
0-3.00	0	3.670-3.7405	50
3-3.140	5	3.7405-3.7755	55
3.140-3.240	10	3.7755-3.812	60
3.240-3.350	15	3.812-3.847	65
3.350-3.430	20	3.847-3.983	70
3.430-3.505	25	3.983-3.945	80
3.505-3.565	30	3.945-3.990	85
3.565-3.618	35	3.990-4.050	90
3.618-3.658	40	4.100-4.200	100
3.658-3.670	45		

The wide range in 0% SOC is because li-ion battery is considered empty at 3.0V

3. TEST AND RESULT

The test carried out focused on SOH, SOC and the temperature of the battery during charging. The values used for SOC is shown in Table 4. SOC of the three (3) batteries are set at different levels.

Table 4 Initial SOC of batteries

	Battery 1	Battery 2	Battery 3
SOC (%)	10	20	30

This is done to show the charging of unbalanced cells/systems, using CCCV profile. The temperatures and thermal energy of the batteries during charging is also tested. During simulation, initial temperature of each battery was kept at 20^{0}C. The battery voltage and current were measured and the signal is sent to the scope to show the voltage and current of individual battery during charging of the battery pack.

Result from SOC graph showing system balance

The Result of the graph from the measurement of SOC of individual battery cells is shown in Figure 7.

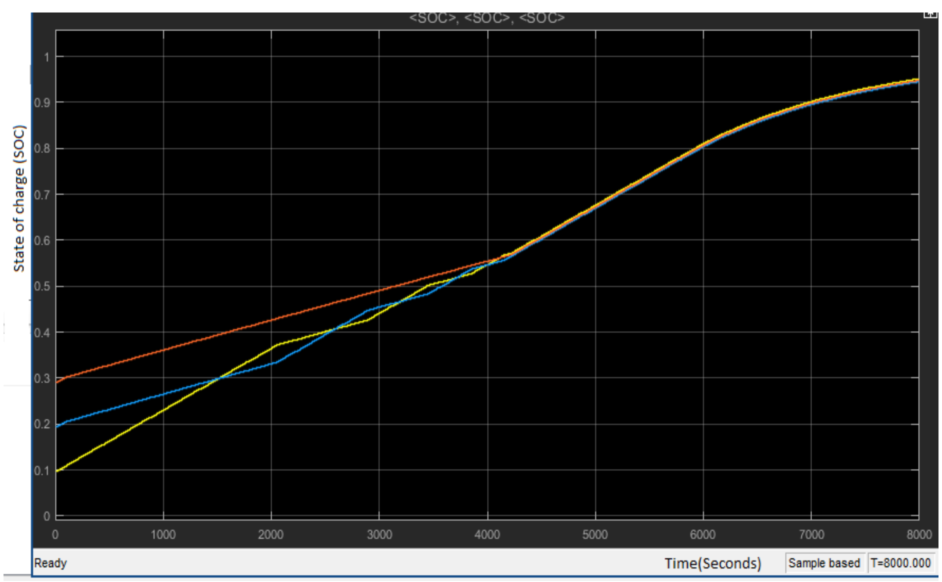


Figure 7 Graph of SOC of the Battery Pack.

From the graph, it shows that first second and third battery of SOC was set at 10%, 20% and 30%. Simulation time is 8000 seconds. The red, blue and yellow colored plots represent batteries/cells with 30%, 20% and 10% initial SOC respectively. For the battery with initial SOC of 30%; from time 0 to 4000 seconds, SOC increased linearly from 30% to 55%. The battery with initial SOC

of 20% had three stages of increment from time 0 – 4000 seconds. It exhibited gradual and linear increment in SOC from 20% to 32% between times 0 – 2000seconds. Between time 2000 – 2900 seconds there was a steep & linear increment of SOC from 32% to 45%, while at time 2900 - 4000 seconds SOC dropped slightly and then increase from 45% to 55%. In the case of battery/cell with initial SOC of 10%, it had four stages of SOC increment between times 0 – 4000. As seen on the graph, between 0– 4000 seconds, the individual batteries have different SOC. From time 4050 to 8000, the individual batteries have the same SOC. This implies that the balancing was achieved after 4050 seconds. Without the balancing technique, all the batteries may not be charged to the same level and this will lead to early battery pack failure. The plots are logarithmic within this time period.

Temperature and thermal graph

The uneven and intermediate flow of current through each individual cells and also the asymmetrical way which heat flow through the pack causes thermal buildup to be uneven as shown in Fig 8.

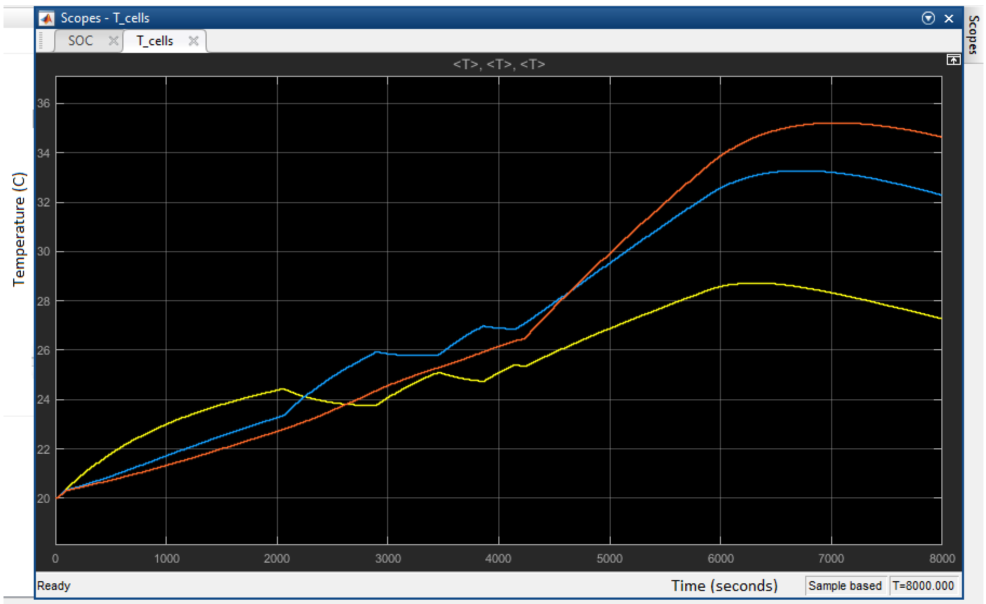


Figure 8 Shows the graph of temperature of individual battery cells.

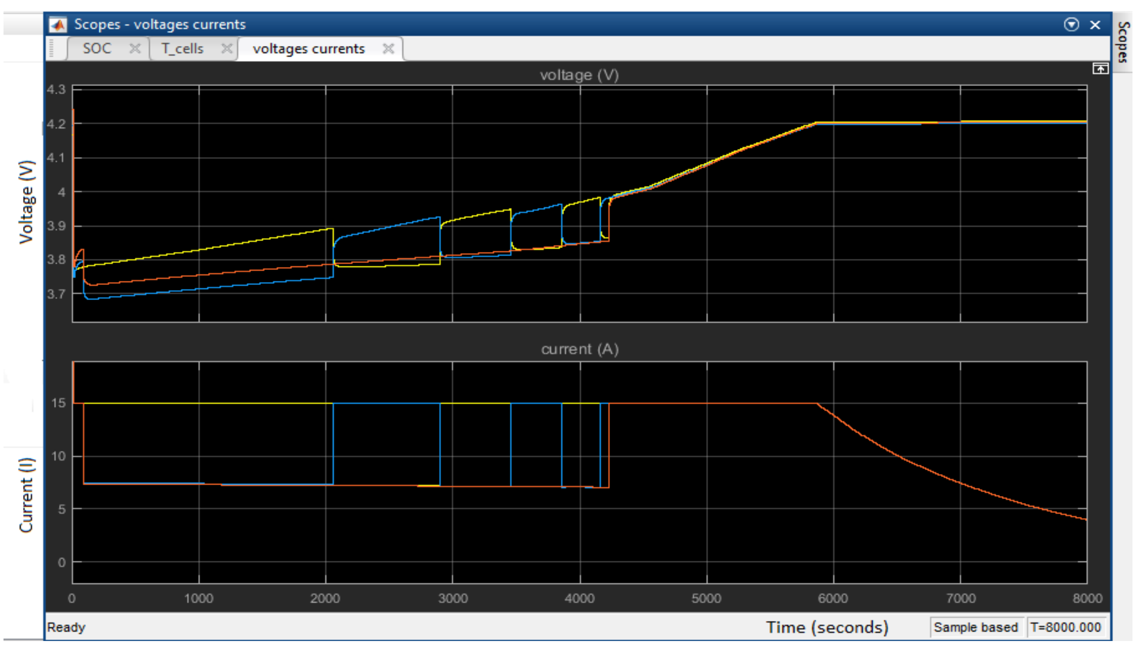


Figure 9 The current and voltage graph of the individual battery cells

The red, blue and yellow colored plots represent batteries/cells with 30%, 20% and 10% initial SOC respectively. The simulation time is 8000 seconds. The three batteries were initially at 20ºC. The graph was divided into three periods; period 1(0 to 2000 seconds), period 2 (2050 to 4100 seconds), and period 3 (4100 to 8000 seconds). In period 1, the temperature of the battery with least SOC of 10% rose exponentially from 20ºC to 25.2ºC while temperature of the batteries with 20% and 30% rose linearly from to 20ºC to 23.1ºC and 22.9ºC respectively. The trend is similar and hence it can be concluded that with temperature rise at commencement of charging, SOC will be lower. In period 2, the batteries have temperature differences within 2ºC. The plots are saw tooth wave implying that the temperatures rise and drop rapidly. During period 3, the temperatures rise logarithmically, reaches a plateau and decrease a little towards end of the charge and balancing process.

Voltage and Current Charging of the Battery

The individual voltage across the battery cells and current flowing through the battery cells is shown in Fig 9.

The simulation period is divided into three periods. Periods 1, 2 and 3 lies between 0-2050 seconds, 2050-4200 seconds, and 4200-8000 seconds respectively. The red, blue and yellow colored plots represent batteries/cells with 30%, 20% and 10% initial SOC respectively. During period 1, the battery voltage with 10% initial SOC was between 3.78 and 3.9, for battery with initial SOC of 30% was between 3.74 and 3.79 while that of 20% initial SOC was between 3.68 and 3.75. Within this period, the battery with initial SOC of 10% had charging current of 15A, while the batteries with initial SOC of 20% and 30% charged with 7.5A. In period 2, the voltage of all the batteries were rising and falling with tooth wave manner. The batteries charging current with initial SOC of 20% and 10% oscillated between 7.5 and 15A while one with initial SOC of 30% remained at 7.5A. During period 3, the battery voltage increased linearly from 3.98 to a plateau of 4.2V at 5800 seconds. The voltage remained constant throughout the remaining simulation time. The charging current of 15A was constant for all the batteries up till 5800 seconds. Current decreased afterwards to under 5A at 8000 seconds.

Result for SOH

To test for SOH, the three batteries were set at an initial SOC of 95%, charged to 100%, and discharged individually to SOC of 80% using uniform load. SOC values for the first discharge from 100% to 80% within 24seconds was captured and shown in Table 5. The charge to 100% SOC and discharge to 80% SOC was run 1800 times within 86,400 seconds. The battery SOC in the 1800th discharge was captured for the last 24 seconds. That is from 86378 -86400 (seconds) simulation time. Values obtained are as shown in Table 6. Comparing the values of SOC's after cycling the li-ion batteries for 1800 times as shown in Table 6 with that of Table 5 (shows SOC's of the batteries before been cycled), the batteries had marginal increase in SOC. This is due to Nernst effect (Equation 2.4) and balancing of the batteries throughout the cycling. The batteries are said to be in good condition because it was still able to deliver power and maintain expected SOC's.

Table 5 SOC's and time for the first discharge of the batteries within 24 seconds

Time (S)	Battery 1 (%)	Battery2 (%)	Battery 3 (%)	Time (S)	Battery 1 (%)	Battery2 (%)	Battery 3 (%)
1.000	99.1667	99.1667	99.1667	13.000	89.1671	89.1671	89.1671
2.000	98.3334	98.3334	98.3334	14.000	88.3338	88.3338	88.3338
3.000	97.5001	97.5001	97.5001	15.000	87.5005	87.5005	87.5005
4.000	96.6668	96.6668	96.6668	16.000	86.6672	86.6672	86.6672
5.000	95.8335	95.8335	95.8335	17.000	85.8339	85.8339	85.8339
6.000	95.0002	95.0002	95.0002	18.000	85.0006	85.0006	85.0006
7.000	94.1669	94.1669	94.1669	19.000	84.1673	84.1673	84.1673
8.000	93.3336	93.3336	93.3336	20.000	83.3340	83.3340	83.3340
9.000	92.5003	92.5003	92.5003	21.000	82.5007	82.5007	82.5007
10.000	91.6670	91.6670	91.6670	22.000	81.6674	81.6674	81.6674
11.000	90.8337	90.8337	90.8337	23.000	80.8341	80.8341	80.8341
12.000	90.0004	90.0004	90.0004	24.000	80.0008	80.0008	80.0008

Table 6 SOC's for the last 24 seconds of the 86,400 seconds simulation

Time (S)	Battery 1 (%)	Battery 2 (%)	Battery 3 (%)	Time (S)	Battery 1 (%)	Battery 2 (%)	Battery 3 (%)
86378	99.920100	99.902000	99.993000	86390	90.380148	89.951000	89.994600
86379	99.125104	99.072750	99.159800	86391	89.585152	89.121750	89.161400

86380	98.330108	98.243500	98.326600	86392	88.790156	88.292500	88.328200
86381	97.535112	97.414250	97.493400	86393	87.995160	87.463250	87.495000
86382	96.740116	96.585000	96.660200	86394	87.200164	86.634000	86.661800
86383	95.945120	95.755750	95.827000	86395	86.405168	85.804750	85.828600
86384	95.150124	94.926500	94.993800	86396	85.610172	84.975500	84.995400
86385	94.355128	94.097250	94.160600	86397	84.815176	84.146250	84.162200
86386	93.560132	93.268000	93.327400	86397	84.020180	83.317000	83.329000
86387	92.765136	92.438750	92.494200	86398	83.225184	82.487750	82.495800
86388	91.970140	91.609500	91.661000	86399	82.430188	81.658500	81.662600
86389	91.175144	90.780250	90.827800	86400	81.635192	80.829250	80.829400

4. DISCUSSION

An optimized Li-ion BMS offers unique and novel solution to the optimum performance of Li-ion battery bank. In the optimized system, a standard bleed resistor and MOSFET that works as a variable resistor were placed across all the individual batteries/cells and are used in rapid balancing of all the batteries in the pack during charging process. MOSFETS are controlled by logic controllers to either increase or decrease its resistance. This affects the real current used in charging a particular battery in the pack. The standard resistors and MOSFETS were also used to estimate the SOH of each battery. The three batteries for the simulation were assumed to have initial SOC's of 10%, 20% and 30%. The red plot represents the battery with initial SOC of 30%, while blue and yellow plots represent batteries with initial SOC's of 20%and 10% percent respectively. Simulation times of 8000 seconds were used. A look up table generated from the battery (shown in Table 5) and cell balancing logic were programmed into the logic controller. During charging and balancing process as shown in Figure 7, for the battery with initial SOC of 30%, from time 0 – 4000, SOC increased linearly from 30% to 55%. The battery with initial SOC of 20% had three stages of increment from time 0 – 4000. It exhibited gradualand linear increment in SOC from 20% to 32% between 0 – 2000 seconds. Between 2000 – 2900 seconds there was a steep and linear increase of SOC from 32% to 45%, while at time 2900 - 4000 seconds there was exponential increase in SOC from 45% to 55%. In the case of battery/cell with initial SOC of 10%, it had four stages of SOC increment between 0s – 4000s. As seen on the graph, from 0s – 4000s, the individual batteries have different SOCs. From 4050s- 8000s, the individual batteries have the same SOC. The foregoing posits that battery SOC balancing is achieved within 0 to 4000 seconds. The non-uniform variations among the three batteries are due to fast variation of the current that enters the battery by the MOSFETs based on instruction from the logic controller. This approach is faster than the regular bleed resistor balancing system that stops charging process till the SOC's of the higher charged batteries are reduced to SOC of the lower charged one(s). This is achieved by running of the charge as heat through the bleed resistor(s). The overall plots are similar to plot of logarithmic function which is the standard Li-ion charging profile.

Between 0s to 2000s, battery temperature with least SOC of 10% rose exponentially from 20ºC to 25.2ºC while temperature of the batteries with 20% and 30% rose linearly from 20ºC to 23.1ºC and 22.9ºC respectively. The trend is similar, and it can be inferred that the lower the SOC of a battery, the higher the temperature rise at commencement of charging. At simulation time of 2050s to 4100 seconds, the batteries have temperature differences within 2ºC. The plots are saw tooth wave implying that the temperatures rise and drop rapidly. From 4100 seconds to end of the simulation, the temperatures rise logarithmically, reaches a plateau and decreases till end of the simulation time. This marks end of the charge process. SOH of the battery were good after cycling them for 1800 times. No significant degradation was observed in the batteries. This shows that running li-ion battery bank/pack with BMS goes a long way in guaranteeing that it will have an optimum performance throughout the service life.

5. CONCLUSION AND RECOMMENDATION

This work reviewed relevant/related journal articles. Data were also collection and generation of look up table that relate SOC, SOH and cell balance with voltage of Cell/Battery was established. Modeling of cell/battery as well as design and simulation of BMS was done. System testing (Measuring/deducing of SOC, SOH, temperature and battery balancing) as well as Validation of results obtained were done in the cause of the investigation. It should be noted that while charging the batteries, SOC of the battery with initial value of 30%, increases linearly from 35 to 55%. The battery with initial SOC of 20% had three stages of increment while the battery with initial SOC of 10% had four stages of increment. At 4050 seconds, the batteries were balanced. Without the balancing they will not be at the same SOC. Some batteries may be overcharged or undercharged. Temperature increased from 20ºC to 25.2ºC, 20ºC to 23.1ºC, 20ºC to 22.9ºC for batteries with initial SOC's of 10%, 20% and 30% respectively. This temperature increase occurred before balancing the process. During balancing, the temperature differences of batteries in the pack were within 2ºC. After battery balancing, temperature increased logarithmically, reached a plateau of 35ºC and decreased towards end of the charging process. The lower the SOC of li-ion battery the higher the heat it will emit during charging. So care should be taken while charging a fully

drained li-ion battery. Before balancing, the battery with initial SOC of 10% charged with 15A, 3.78V - 3.9V, for battery with initial SOC of 20% it charged with 7.5A, 3.68 – 3.79V, while that of 30% initial SOC charged with 7.5A, 3.74 –3.79V power. During balancing, the current was fluctuating between 7.5A and 15A in a saw tooth manner. At 5800 seconds, the batteries were balanced and charging with 15A. The current decreased to 5A at 8000 seconds. The logic controller is efficient in controlling the real charging through the MOSFET and standard resistor. BMS with the novel balancing technique ensured optimum performance of li-ion battery bank throughout its service life. Nernst equation is valid for li-ion battery cycle several times. The heat and temperature rise that accompanies the cycling makes SOC to appear higher than the real SOC.

It is recommended that a physical work bench that can charge and discharge the batteries 1800 times within 86400 seconds in a fume chamber should be explored to validate the influence of Nernst equation on SOC.

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